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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (4): 604-613, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.604.613

The Design of Vertical Axis Wind Turbine Rotor for Antarctic

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Abstract: While wind power (WP) is a popular research issue in vigorously promoting green energy era, the research of the utilization of wind energy based on Antarctic moving platforms is still rarely involved. In this study, a kind of rotor for Vertical Axis Wind Turbine (VAWTs) was introduced which is first equipped on a moving platform for Antarctic's exploring. The fluid simulation software Fluent was used to analyze and compare the performance of four different airfoil shape of wind turbine. To reduce the number of times of simulation and trial effectively, the uniform optimal design method was adopt to optimize the parameters of the radius of rotor, blades number, blade chord length and blade installation angle and the values of various parameters of the wind rotor and the efficiency of wind power affected by the complex influence of the four factors were obtained. Finally, the wind hub structure and materials were analyzed with ANSYS software and by the static and modal analysis, the reliability of the wind turbine in strong wind was verified which laid the foundation for the producing of wind turbine with higher efficiency in the future.

Key words: Wind turbine, rotor, uniform optimal design, hub, static analysis, computational fluid dynamics

INTRODUCTION

The use of wind power far earlier than the invention of internal combustion engines wind-driven ships were used (Kurtulmus *et al*., 2007). Since the environmental problems occurred in the late 20th century, people began to pay attention to the use of the clean and renewable energies (Vardar and Eker, 2006). Wind power is one of the fastest developing and low-cost industry which is a renewable energy utilization way. However, climate has a great influence on the generation of the wind power (Meng and Song, 2007). Antarctic, the average wind speed is high and low temperature, therefore, the worldwide concern about environmental pollution and possible energy shortage has led to increasing interest in generation of renewable electrical energy (Babainejad and Keypour, 2010).

Wind turbine can be divided into Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbin (VAWTs) two categories by different rotor shaft which are used mainly for electricity generation (Izli *et al*., 2007), VAWTs have inherent advantages, the principal advantages of the vertical axis format are their ability to accept wind from any direction without yawing and the ability to provide direct rotary drive to a fixed load (Beri and Yao, 2011). Compares with HAWTs, VAWTs have strong resisting wind ability. In addition, the noise of VAWTs is much smaller.

This study aims to research and develop a first-fit VAWTs rotor used under Antarctic's extreme climate which is adopted to provide energy for the Antarctic expedition car's electronic equipment, on the condition that the wind turbine can work properly to produce electric power, while not affect the normal work of the instrument in the Antarctic's extreme environment. At the same time, its structure should be light weight, small volume and high efficiency of power generation. Therefore, a kind of VAWTs rotor was tried to be designed.

WIND TURBINE ROTOR

The blades which are mounted on the hub are called the wind rotor which mainly includes the blade, the hub, the shaft, etc. The wind rotor is the most important unit to turn wind energy into mechanical energy which directly determine the success of the wind turbine system (Niu and Zhang, 2007; Paraschivoiu, 2002).

Main technical indexes: It requires that the wind rotor output energy with high efficiency to meet 50 W energy supply for the electronic devices in the mobile platform. Because of extremely low average temperature in the Antarctic, the wind rotor is required to work normally in cold condition with temperature from -50 to 50°C. The Antarctic is also an area with the strongest wind power on

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the earth, so the wind rotor is required to work high efficiently when average wind speed is 17 m $\sec^{-1}$; The electric generator should work properly through the mechanical braking adjustment when the wind speed exceeds 17 m $\sec^{-1}$, if the wind speed exceeds 40 m $\sec^{-1}$, the wind turbine stopped because of the mechanical brake. Wind generator with heavy weight will seriously affect the state of motion of the car, so the rotor's total weight should not exceed more than 2% of the weight of the car.

Material: The harsh natural environment of the Antarctic requires the high demands of the wind rotor material, including high strength, high stiffness, low density, long life, good corrosion resistance, especially low temperature tolerance. Some researchers compared the properties of the commonly used materials in wind turbine (Zhang and Ren, 2008), as shown in Table 1.

As can be seen from the Table 1, the density of the composite wood is the smallest, carbon fiber followed. The tensile strength of aluminum alloy is 0.41 GPa which is similar to the alloy steel and carbon fiber. The fatigue strength of carbon fiber is 100 MPa. Although, the density of the composite wood is small, there is a large gap between the strength, fatigue characteristics with the other three materials. The composite materials such as carbon fiber and aluminum alloys have better performance, they have lower density, better fatigue properties and damping properties.

Blade airfoil, hub and spindle: Blade is the key component of the wind turbine and the blade airfoil design is especially important which directly determine the ability to obtain the desired power. So far, spacecraft airfoil is frequent used on the VAWTs, its technology is mature, with large lift coefficient and small drag coefficient characteristics, such as the American's NACA, NASA series. Hub connect the blade and spindle which is the part that most prone to cause cyclic loading fatigue. Hub bear the weight of the blade, the circumferential bending force, plus the tension and pressure force, these forces are very complex, therefore it needs to focus on analysis of the hub structure and force. The shaft and the generator directly connected together by the spindle, it is the main load-bearing component of the entire wind turbine to withstand greater torque, generally made from high-strength alloy steel. Meanwhile, a reliable connection of the spindle with the hub have a major impact on the efficiency of the blade transmitted to the torque coefficient of the spindle.

Table 1: The properties of the four materials

Materials	Density ($g\ cm^{-3}$)	Tensile strength (GPa)	Fatigue strength (MPa)
Alloy steel	7.85	0.450	70
Aluminum alloy	2.70	0.410	40
Carbon fiber	1.40	0.380	100
Composite wood	0.58	0.105	35

SIMULATION OF THE AERODYNAMIC PERFORMANCE OF THE WIND ROTOR

Basic theory of wind turbine: Betz theory is the basic theory of the wind turbine, wind turbine power's estimate should be compared with its maximum power by calculation (He, 2006). Betz theory discuss the maximum wind energy utilization efficiency by applying of the steady flow momentum equation. It assume that the wind rotor is ideal and it accept all wind (no hub). The blades are enough and have almost no resistance to the air flow which is uniformly, continuously and exclude compressible. Consequently, this is a pure energy converter. It also further assumed that the wind rotor swept surface of airflow direction in terms of the wind rotor around or through are perpendicular to the blade sweep surface. On this condition, the impeller is called the "ideal impeller" which resulting in wind energy utilization coefficient Cp:

$$C_p = \frac{P}{\frac{1}{2}\rho S v_1^3} \tag{1}$$

In the formula, ρ is the air density (kg m^{-3}), P is wind rotor power (W), S is wind rotor swept area (m^2), v_1 is the wind speed (m $\sec^{-1}$). The design constraints of the wind rotor is the pursuit of the proportion of the wind turbine output power obtained from natural wind. Ideal wind rotor wind energy utilization factor $Cp_{max} = 16/27 = 0.593$, it is the maximum efficiency of the mechanical energy turned out by wind rotor.

Another basic theory of the wind turbine is blade element theory whose basic starting point is to divide the wind turbine blade into a number of micro-segments and these micro-segments is called blade element. Assuming the flow between each blade element are not interfere, in other words, blade element can be seen as a two-dimensional airfoil (Zhang, 2007).

To study the forces of the blade, a cross-sectional view taken on the blade to analyze the force and torque acting on the blade element. The force analysis of blade element shown in Fig. 1:

$$dF_L = \frac{1}{2}\rho c W^2 C_L dr \tag{2}$$

$$dF_D = \frac{1}{2}\rho c W^2 C_D dr \tag{3}$$

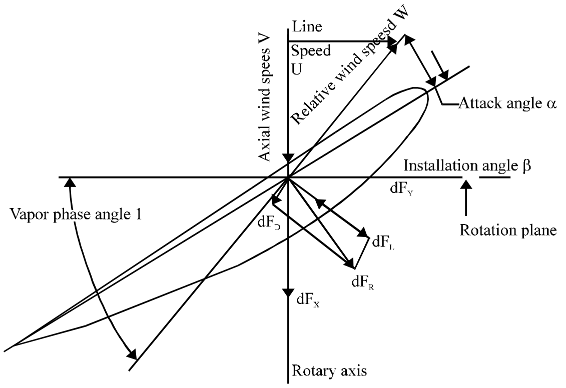

Fig. 1: The force analysis of blade element

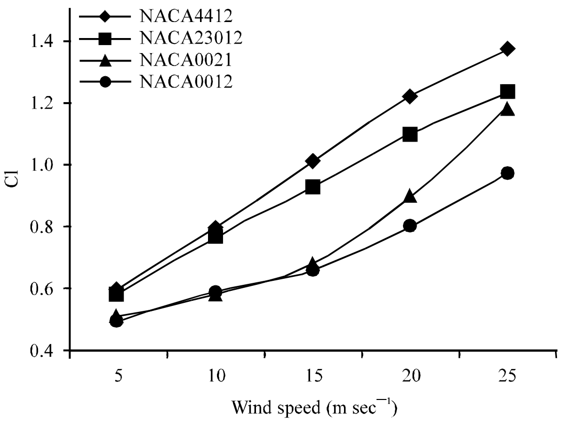

Fig. 2: The C_L for four kinds of airfoils under the same wind speed changes

In the formula, dF_L is the airfoil lift, dF_D is the airfoil resistance, W is the airflow with respect to the blade element of the relative velocity (m sec^{-1}), c is the airfoil chord length, C_L C_D, represent the airfoil lift coefficient and drag coefficient, respectively. DF_L, dF_D is the axial direction and the circumferential projection of the wind rotor, according to Eq. 2 and 3 can be obtained as follows:

$$dF_x = dF_L \cos I + dF_D \sin I = \frac{1}{2}\rho c W^2 dr (C_L \cos I + C_D \sin I) \quad (4)$$

$$dF_y = dF_L \sin I + dF_D \cos I = \frac{1}{2}\rho c W^2 dr (C_L \sin I + C_D \cos I) \quad (5)$$

In the formula, dF_x is the shadow of the projection along the reincarnation shaft of the wind turbine, wherein dF_R is the urging force of airfoil, dF_y is the projection of dF_R along the direction of the rotation plane of the wind rotor, I for vapor phase angle, I = I+β, wherein, i is the airfoil angle of attack, β is the blade install angle.

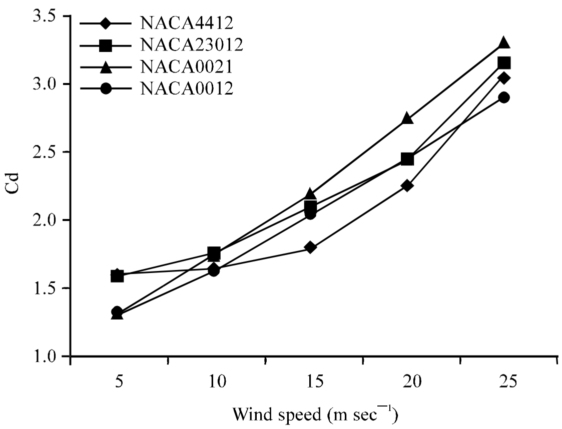

Fig. 3: The C_D for four kinds of airfoils under the same wind speed changes

Because blade element theory is to divide wind turbine blade into a finite number of blade element and then calculate the force and torque on each blade element, integral can obtain the aerodynamic performance of the entire blade can be learned by integral. For blade element force performance, designers' most concern is the power of the blade can be obtained, that is to maximize the utilization efficiency, so airfoil characteristics should be able to meet the three requirements (Ren, 2010): large lift coefficient, low drag coefficient and in the course of the angle of attack changes, the airfoil can maintain excellent aerodynamic performance. Aerodynamics, the theoretical basis in airfoil profile, research experimental data of airfoil profile aerodynamic performance and theoretical calculation methods, provide the foundation of wind turbine the aerodynamic performance research and design.

Airfoil selection: We learned by the blade element theory that the performance of wind turbine greatly affected by the airfoil. When VAWTs wind rotor in the rotation, its radial force and cutting force increase or decrease cyclically. Within one cyclical revolution, the blade torque coefficient is also changing. Airfoil design is a very complex subject since it involves a lot of knowledge of fluid dynamics. Four groups of wind turbine with special airfoils used widely were chosen to study in this study which is published by the American space agency. They are symmetric airfoil NACA0012, NACA0021 and asymmetrical airfoil NACA4412, NACA23012. We compare and analyze this four airfoil by the Fluent simulation software, choosing 5-25 m sec^{-1} wind speed, the rest of the reference design parameters fixed. Figure 2-5 compares the lift coefficient (C_L), the drag coefficient (C_D), the torque coefficient (C_m) and the lift-drag ratio (C_L/C_D) of four airfoils in different wind speeds.

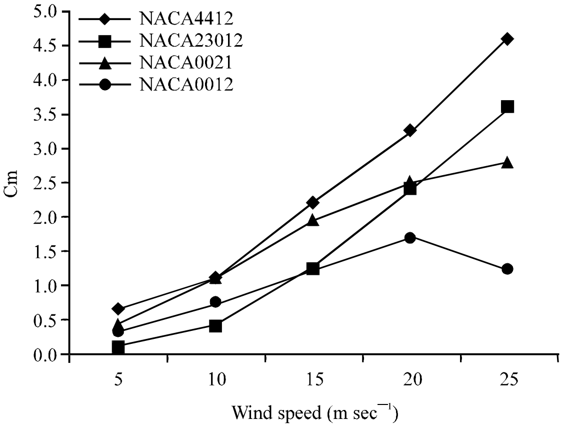

Fig. 4: The C_m for four kinds of airfoils under the same wind speed changes

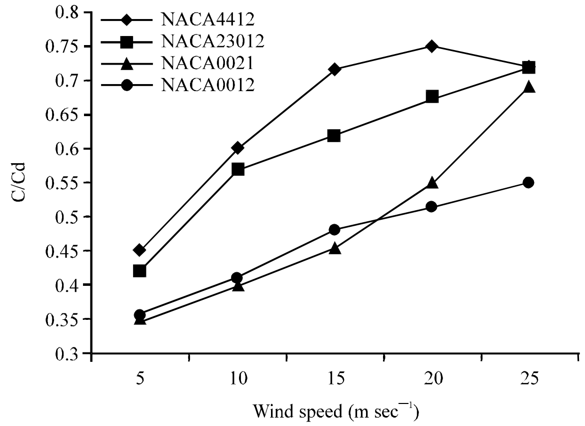

Fig. 5: The C_L/C_D for four kinds of airfoils under the same wind speed changes

Table 2: Wind rotor model parameters and the optimum range

Parameters	Initialization	Optimum range					
Number of blades (a)	5	2	3	4	5		
Chord length (m)	0.12	0.08	0.09	0.10	0.11		
		0.12	0.13	0.14	0.15		
		0.16	0.17	0.18	0.19		
Radius (m)	0.3	0.25	0.30	0.35	0.40	0.45	0.5
Installation angle°	0	-10	-8	-6	-4	-2	0
		2	4	6	8	10	12

As can be seen from Fig. 2-5, different airfoil in the same wind speed change of C_L, C_D, C_m and C_L/C_D trend is the same and its amount has a tendency of increase with increasing wind speed. Figure 2 shows that the wind conditions of the different incoming flow, the four airfoil lift coefficient of a big difference. Wherein the lift coefficient of the airfoil NACA4412 is largest and is much higher than the other airfoils. Figure 3 shows that the drag coefficient of four airfoils has almost no difference and the drag coefficient of airfoil NACA4412 is slightly larger than the other three airfoils in wind speed of the different incoming flow. Figure 4 shows that under the wind speed of the different incoming flow, the torque coefficient of airfoil NACA4412 is the largest and the torque coefficient of airfoil NACA0012 is the smallest. Figure 5 shows that under the wind speed of the different incoming flow, the lift to drag ratio of the airfoil NACA4412 is the highest and the lift to drag ratio of the airfoil NACA0012 is the smallest. Therefore aerodynamic performance of the airfoil NACA4412 is better than the other airfoil, NACA0021 followed, the NACA0012 is the worst. So choosing NACA4412 asymmetric airfoil as the research subject and provided the reference basis for future design.

Analysis of the aerodynamic performance of wind rotor

Wind rotor model: Many factors affect wind energy utilization of wind rotor. This study focuses on the number of the blades, blade radius, airfoil chord length and blade installation angle as optimization parameters. The choice of the number of the blades select 2 to 6 according to wind rotor solidity. Currently, there is no specific theoretical support for the choice of the airfoil chord length, so the choice of chord length refer to the mature wind turbine, changes from 0.08 to 0.19. Wind rotor radius is determined by the mobile platform size, changing from 0.25 to 0.5. Installation angle changing from 10 to 12° . The specific parameters of wind rotor as shown in Table 2. Rated wind speed is set to the average wind speed in the Antarctic, namely 17 m sec^{-1}. Using better performance airfoil NACA4412 modeling, Computational Fluid Dynamics (CFD) simulation for both two-dimensional model to obtain the output of the wind rotor torque under different parameters and wind energy utilization factor and then find the optimal parameters and is currently the most comprehensive and the most widely used CFD software.

This article uses Fluent software to simulate and take the second-order upwind SIMPLEC algorithm solver in 2D unsteady Reynolds-averaged Naiver-Stokes equations to calculate and selects the Spalart-Allmaras turbulence model. Using moving mesh technology to deal with the rotation of the wind rotor. For a number of different blades, blade chord length, radius of the wind rotor and installation angle, the numerical simulation of wind rotor is completed. At the same time, this article analyzes the flow field characteristics and gets the individual parameter values in the maximum of the wind energy utilization.

Uniform optimization method in the application of the design: This design considers a number of factors of wind turbine size changes, so there are a lot of conditions need to calculate, thus the uniform optimization design method was introduced. Uniform design theory is proposed by

Table 3: The VAWTs concrete size and the number of levels given by the uniform table

Chord length	Radius	No. of blades	Installation angle	Wind energy utilizing rate (%)
0.13	0.25	4	8	12.6
0.19	0.25	2	-2	10.1
0.12	0.30	5	-4	18.9
0.18	0.30	3	-10	23.8
0.11	0.35	2	10	24.7
0.17	0.35	4	4	22.9
0.10	0.40	3	2	20.0
0.16	0.40	5	-8	28.2
0.09	0.45	4	12	24.2
0.15	0.45	2	-6	35.2
0.08	0.50	5	0	22.7
0.14	0.50	3	6	36.1

Fang Kaitai, The theory is a design method which just considers the test points uniformly distributed within the test range. It is a test method that applies to multi-factor and multi-level as well. Compared with the traditional method that test points were evenly spread regardless of neat comparable orthogonal design, the uniform design method can greatly reduce the number of trials. For a selected number of tests, factor in the number and level number, uniform design table already exists and can be used directly. Table 3 is the VAWTs concrete size and the number of levels given by the uniform table, By Fluent software to numerical simulation of various conditions, select the parameter values of the largest wind energy utilization.

From the Table 3, we can get the initial the wind energy utilizing rate increases significantly with increasing radius of the wind rotor, this also applies to the chord length. Within a certain range, the installation angle of a relatively small impact on the wind energy utilization. With the increase of blades, lower utilization of wind energy. This design adopt uniform optimal design method, only 12 times of the numerical simulation was taken and the various parameters of the wind rotor of wind energy utilization can be found. The wind energy utilization close to literature (Zhou, 2009) but significantly reduced the number of trials. The statistical results in Table 3 can be found in the airfoil NACA4412 in the case of an optimal set of design parameters, i.e. The radius is 0.5 m, the blade chord length is 0.14 m, the installation angle is 6°, the number of the blades is 3, wind utilization efficiency is 36.1%. Subsequent work requires the test data for statistical processing, so as to extract more useful information. It provide a basis for building a physical model which is of great significance to further wind turbine design.

HUB MATERIAL SELECTION AND HUB STRUCTURE

Plan selection: VAWTs' high torque fluctuations with each revolution, no self-starting capability are the drawbacks (Islam *et al.*, 2008). The worlds of David Darling (2009). The stability requirement of hub structure is particularly important in the bad environment of the Antarctic. The design chooses two common hub structures in market, they are the triangular structure (Fig. 6) and square structure (Fig. 7). Figure 6 is the three dimensional model created by Pro/E 3D software. By using ANYSY software to get static analysis and modal analysis. Then to select the best hub material and structure theoretically.

Table 4: Triangular structure hub of maximum displacement and stress simulation results

Material	Maximum displacement (mm)	Yield strength (MPa)	Maximum stress (MPa)
Carbon fiber	0.2146	2450	73.809
Aluminum alloy	0.7257	280	65.049
Stainless steel	0.3816	207	88.762
Structural steel	0.3727	250	90.045

Table 5: Square structure hub of maximum displacement and stress simulation results

Material	Maximum displacement (mm)	Maximum stress (MPa)	Yield strength (MPa)
Carbon fiber	0.34	17.209	2450
Aluminum alloy	1.39	14.307	280
Stainless steel	0.69	19.438	207
Structural steel	0.67	19.513	250

The static analysis of hub structure: The average wind speed of Antarctic is 17 m $\sec^{-1}$, depending on the wind formula WP = $v^2/1600$ (kN m^{-2}), the wind pressure WP = 180 Pa, Select the wind pressure direction perpendicular to a blade and static analysis of the wind turbine. Assume that the wind turbine blade material is a carbon fiber, the density ρ = 1.4 g cm^{-3}, its gravity approximately G = 20 N. According to these two programs, the wind turbine model draw in the Pro/E software, corresponding load and fixed constraints applied to the model at the same time. Four materials chosen for the wind turbine hub, carbon fiber, aluminum, stainless steel and structural were compared and analyzed. The four materials total deformation simulation cloud picture shown in Fig. 8-11. The triangular structure hub maximum displacement and stress simulation results are shown in Table 4. According to the chart data, we known the maximum stress is much less than the respective yield strength, not exceeding the allowable stress. The amount of deformation of the carbon fiber is 0.2146 mm and it is the smallest in the four materials.

The four materials total deformation simulation cloud picture shown in Fig. 12-15. Square structure of the hub maximum displacement and stress simulation results are shown in Table 5. According to the chart data, the maximum stress is much less than the respective yield strength. The amount of deformation of the carbon fiber is 0.34 mm and it is the smallest in the four materials.

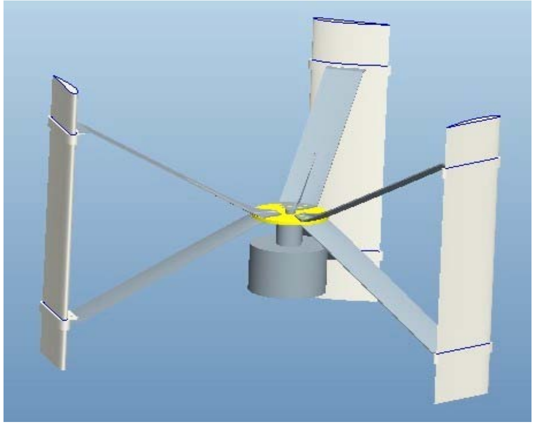

Fig. 6: The model of triangle hub structure selected in the market

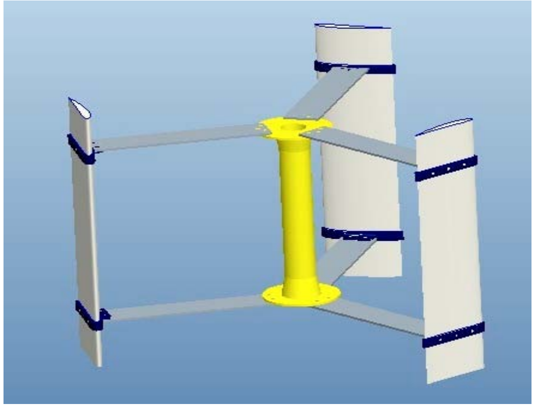

Fig. 7: The model of square hub structure selected in the market

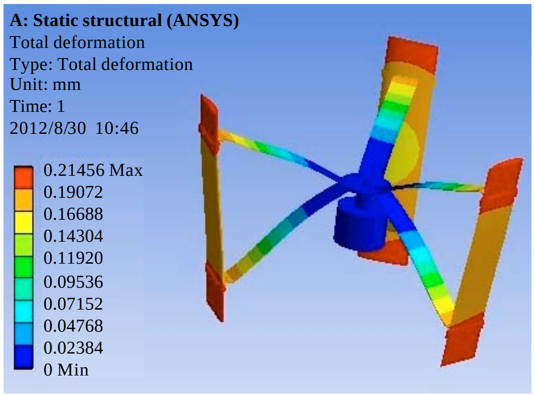

Fig. 8: The displacement simulation results of triangular structure hub by using carbon fiber

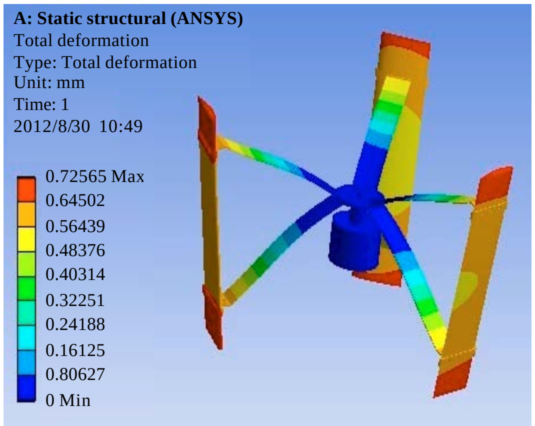

Fig. 9: The displacement simulation results of triangular structure hub by using aluminum alloy

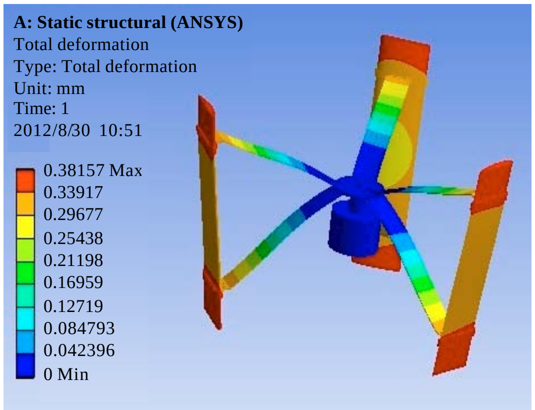

Fig. 10: The displacement simulation results of triangular structure hub by using staiuless steel

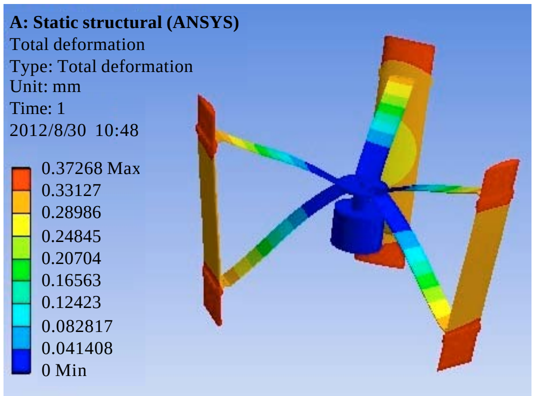

Fig. 11: The displacement simulation results of triangular structure hub by using structural steel

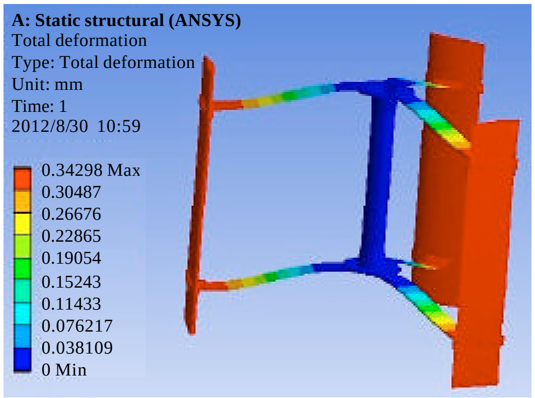

Fig. 12: The displacement simulation results of square structure hub by using carbon fiber

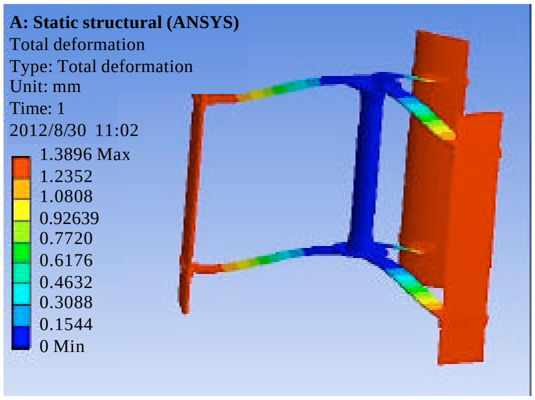

Fig. 13: The displacement simulation results of square structure hub by using aluminum alloy

Analysis by the above simulation, compared the displacement of the two different materials under the triangular structure of the hub and the square structure of the hub, when the material is carbon fiber, the deformation of the displacement value to the minimum, so the material of carbon fiber used for the wind turbine hub is more appropriate in the theoretically. In the case of the four different materials, the deformation volume of the triangular structure is smaller than the square structure, so the wind turbine hub structure using the triangular structure is more appropriate.

Modal analysis of the blades and hub: When the wind generator is running, the blade's displacement occurred under the force produced by the wind, the self-gravity, centripetal force and so on. So it is necessary to verify the natural frequency of the wind hub (Divya and Nagendra Rao, 2006).

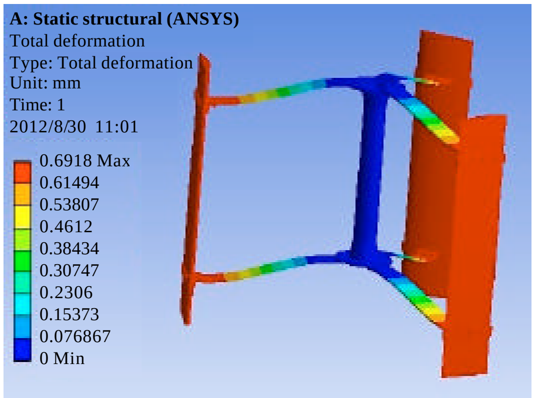

Fig. 14: The displacement simulation results of square structure hub by using stainless steel

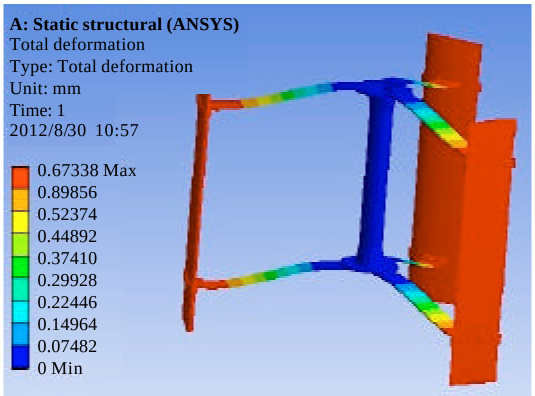

Fig. 15: The displacement simulation results of square structure hub by using structural steel

Modal analysis of triangular structure: When the material is carbon fiber and the hub is a triangular structure, it is the natural frequency of the six modes as shown in Fig. 16-21. From that we can know that the six orders of the natural frequency are 34.942, 34.985, 35.549, 79.772, 115.06 and 115.19, respectively. The 1, 2 and 3 order are similar. 5 order natural frequency and 6 order natural frequency are similar. This is due to the three groups of blades and the blade strut distribution are 120° and the first 3 order of their respective vibration modes in the XZ plane.

RESULTS AND DISCUSSION

In the fixed-speed wind turbine design, the wind rotor rotation frequency is the most important factor. This frequency is often defined as "1P", it may induce dynamic load increase, as a result of the wind rotor imbalance. In

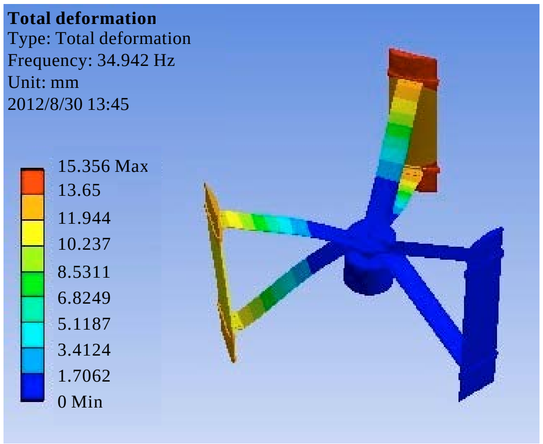

Fig. 16: First order modal vibration diagram

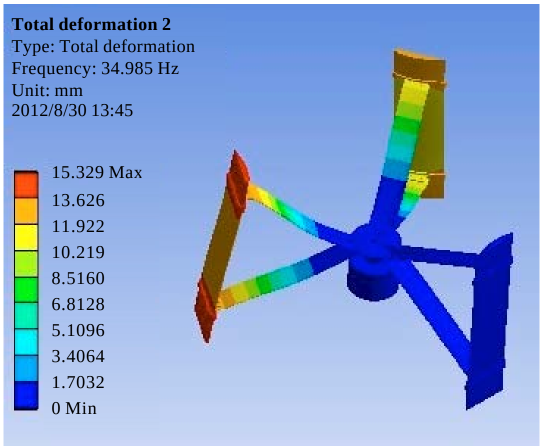

Fig. 17: Second order modal vibration diagram

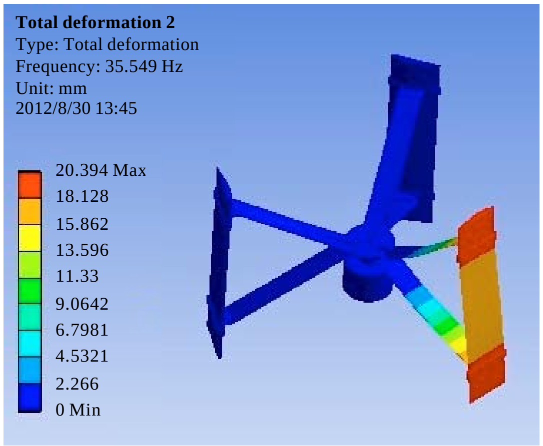

Fig. 18: Third order modal vibration diagram

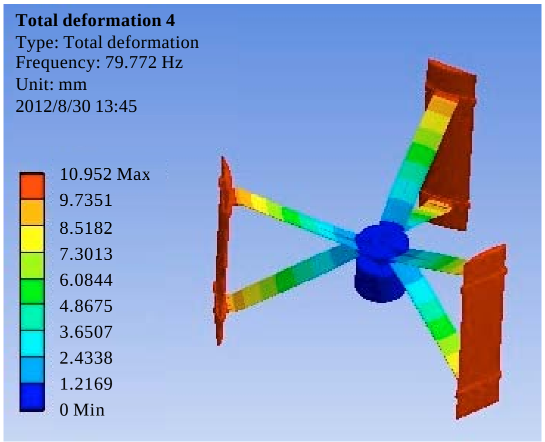

Fig. 19: Fourth order modal vibration diagram

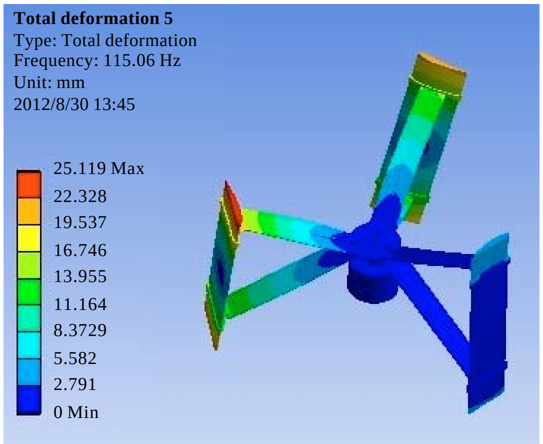

Fig. 20: Fifth order modal vibration diagram

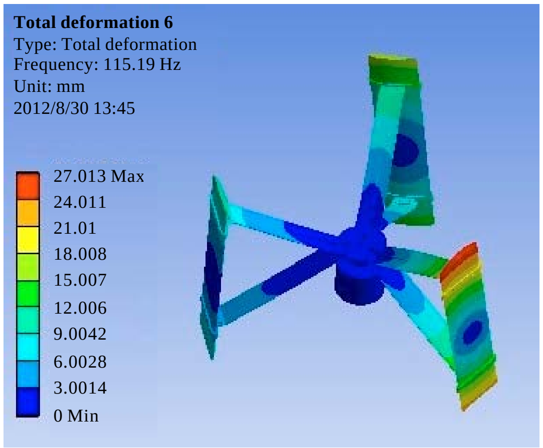

Fig. 21: Sixth order modal vibration diagram

addition, the order of "P" is also very important, as the "2P" and "3P" which correspond to the rotational frequency of the wind turbine blade of the two blades and three blades. In the variable speed wind turbine design, it must make sure that the speed of blades does not close to in the first natural frequency range of the blade model.

In this study, the rated speed of the wind generator model is 400 r min^{-1}. According to the frequency formula:

$$f = \frac{\omega}{2\pi} \times N \quad (6)$$

From the above, the rotational frequency of the wind rotor the f = 20/3 Hz, a single blade passing frequency, $f_0 = 3f = 20$ Hz. Since the natural frequency of the wind model must be outside of ±10% of the wind hub rotational frequency and the individual blade frequencies, it will not cause resonance. By the formula:

$$\frac{|f_0 - f_1|}{f_1} = 42.8\% > 10\% \quad (7)$$

In the formula, f_1 is the first natural frequency. As can be seen, the natural frequency of the triangular structure wind hub model of the carbon fiber is 42.8%. Namely this structure of wind hub model is outside ±10% of the wind hub rotational frequency and the individual blade frequencies. So it is can guarantee the problem of load amplitude will not be caused by the natural frequency.

CONCLUSION

A kind of rotor for VAWTs was introduced in this study. It briefly describe the material, blade, hub and spindle of wind rotor and introduce the basic theory of wind turbine, including Betz theory and blade element theory. Four dedicated wind turbine blade airfoil was studied by the commercial software Fluent, compared with the four blade airfoils of C_L, C_D, C_m and C_L/C_D, then it can be concluded that the aerodynamic performance of NACA4412 airfoil is better than other airfoils. A model of VAWTs rotor is established which considering four parameters of the radius, the number of the blades, the blade chord, the blade install angle of the wind rotor and the impact of the changes on the aerodynamic performance of the wind rotor. It can greatly reduce the number of trials to find a set of optimal design parameters from orthogonal optimization results. Under the optimal design parameters, the wind energy utilization of the wind turbine can up to 36.1%.

By analyzing the small vertical axis wind rotor of four different materials, two different structure of the wind hub static analysis by the finite element software analyzes, it calculate out the carbon fiber is more suitable for wind hub. In four different materials, the hub structure is more appropriate to use triangular structure. Calculating the frequency of wind hub's first six order, We learn that it will not produce resonance and therefore the additional load caused by resonance problem does not occur in normal circumstances, the system is secure.

ACKNOWLEDGMENTS

This study is supported by National 863 Program of China (Grant No. 2011AA04Z0202) and Innovation Fund of Shanghai University (Grant SHUCX120080).

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